VOLUME XXI NUMBER 1 WHOLE NUMBER 161

THE JOURNAL
OF
THE ROYAL ASTRONOMICAL SOCIETY OF CANADA

DEVOTED TO THE ADVANCEMENT OF ASTRONOMY AND ALLIED SCIENCES

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PUBLISHED MONTHLY
(*Ten numbers per year*)

January, 1927

PRINTED FOR THE SOCIETY
TORONTO: 198 COLLEGE ST.
FOREIGN AGENTS: WHELDON & WESLEY LTD.
2-4 ARTHUR STREET, NEW OXFORD STREET, LONDON, W.C.2

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THE MOTION OF THE PSEUDO-CEPHEIDS.

BY F. HENROTEAU.

In a former article in this Journal[1], it was shown that, in distribution, the bright pseudo-cepheids lie approximately along the Milky Way, including the two wide branches of the fork.

No doubt in these pseudo-cepheids, which are super-giant stars with a considerable absolute brightness, we are beginning to leave what may be called the local cluster of stars surrounding our Sun, and are at the threshold of this immense super-structure, the Milky Way, or our Sidereal Universe.

Kapteyn's two star steams[2] derived from the study of proper motions, only concerns the local cluster. It would thus be of extreme interest to penetrate further into the greater cosmical system of stars, and find out something with some degree of certainty about general motions. Since the consideration of spiral nebulæ as immense outside cosmical systems, due to researches of several scientists such as H. D. Curtis, Slipher, Lundmark, and Hubble, it is pertinent to pursue further the old question whether our Sidereal Universe is also a spiral nebula. Should there be an indication of spiral motion among the pseudo-cepheids?

The proper motions of pseudo-cepheids are so small that it is impossible to rely upon them to study general motions. The radial velocities offer a better basis of investigation. The mean radial velocities for most of the pseudo-cepheids, obtained either

[1]J.R.A.S. Canada, vol. 19, 1925, p. 237.
[2]Publ. of the Astr. Lab. at Groningen, No. 5.

at Mt. Wilson or at Victoria, were thus collected and corrected for the motion of the solar system in space. It was assumed that the stationary clouds of calcium as revealed by the detached *H* and *K* lines, were on the whole at rest with reference to the galaxy and reflected the exact motion of the Sun; this was originally suggested by the writer[3] and is supported by the researches of J. S. Plaskett, H. Kienle[4], and Otto Struve[5].

The best elements of the solar motion with respect to the calcium clouds, as obtained by Strömberg, are:

A 276°
D +37°
V⊙ 20.1 km./sec.

Using these elements, the following absolute radial velocities were derived:

ABSOLUTE RADIAL VELOCITIES OF PSEUDO-CEPHEIDS.

Star.	Gal. Long.	Gal. Lat.	Velocity. km.
76 Piscium	94°39′	−31°12′	+22.7
14 Persei	111 2	−14 22	− 5.8
17 Persei	117 0	−21 47	+15.2
α Persei	114 9	− 6 5	− 4.3
58 Persei	129 16	− 3 58	+ 7.9
β Camelop.	116 45	+11 12	− 4.6
α Leporis	188 30	−24 1	+42.8
46 Aurigae	132 32	+16 23	+ 7.3
ε Gemin.	156 47	+10 19	+22.2
41 Gemin.	166 25	+10 2	+33.3
δ Can. Maj.	205 50	− 7 4	+55.0
ξ Puppis	209° 4′	+ 1°47′	+22.9
ρ Puppis	210 41	+ 5 38	+64.2
29 Monoc.	191 45	+16 52	+44.1
Boss 2437	150 55	+42 47	+20.1
9 Draconis	87 52	+49 49	−43.4
Boss 3740	44 27	+61 38	−63.3
2 Serpentis	325 53	+47 59	−43.5
Boss 3860	5 7	+58 13	−30.7

[3]J.R.A.S. Canada, vol. 14, 1920, p. 234.
[4]Seeliger Festschrift, p. 38.
[5]Pop. Astr., vol. 33, 1925, p. 641.

ABSOLUTE RADIAL VELOCITIES OF PSEUDO--CEPHEIDS—Cont.

Star.	Gal. Long.	Gal. Lat.	Velocity km.
Boss 4207	5° 7′	+38°50′	+ 0.1
Boss 4329	11 49	+32 41	− 5.4
β Draconis	46 50	+32 9	−39.1
θ Herculis	30 27	+25 58	−46.8
105 Herculis	19 16	+16 26	−19.1
Boss 4795	40 5	+16 30	−29.5
λ Lyrae	30 27	+11 11	−35.0
π Sagittarii	343 8	−14 4	−20.8
θ Lyrae	37 26	+10 40	−50.1
α^1 Capricorni	0 0	−25 40	−36.7
Boss 5205	45 5	+ 1 33	−40.1
35 Cygni	40 53	− 1 47	−22.5
γ Cygni	45 34	+ 0 38	−25.5
ρ Capricorni	353 43	−30 16	+11.6
41 Cygni	38 23	− 6 19	−36.5
α Cygni	51 41	+ 0 48	−21.9
Boss 5416	49 45	− 5 51	−27.2
ξ Cygni	53 25	− 3 13	−36.3
σ Cygni	51 45	− 7 59	−23.8
Boss 5472	63 23	+ 3 33	−35.1
ζ Capricorni	354 16	−44 31	− 3.6
β Aquarii	14 45	−39 8	− 2.9
γ Capricorni	0 0	−45 44	−37.7
ϵ Pegasi	33 4	−32 41	− 7.6
α Aquarii	27 15	−43 14	− 1.8
ζ Cephei	70 29	+ 0 4	−33.0
Boss 5797	41 50	−41 14	−39.0
5 Lacertae	67 18	− 9 44	−25.8
56 Pegasi	62 52	−32 49	−35.2
89 Aquaril	356 25	−67 40	− 4.7
ρ Cassiop.	80 9	− 4 39	−52.9

These values are plotted on the stereographic map represented in figure 1.

A glance at this map shows that in general radial velocities of stars situated in the same region of the sky are of the same order of magnitude. They are all positive on the right, decrease to zero toward the centre and become negative toward the left. In the Cygnus region, where the pseudo-cepheids are greatly condensed, the mean radial velocity is approximatively −30 km.

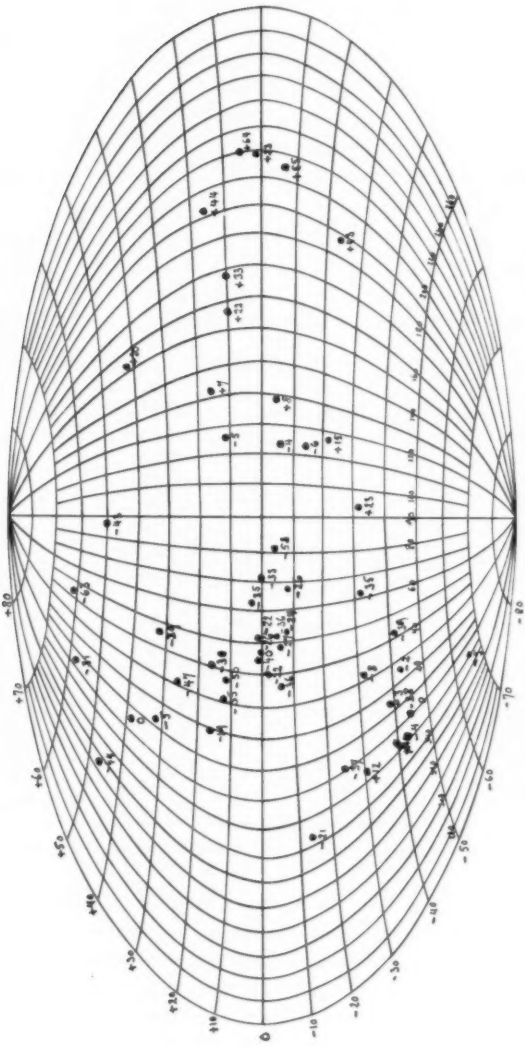

Fig. 1.—Absolute Radial Velocities of Pseudo-Cepheids—Galactic Distribution

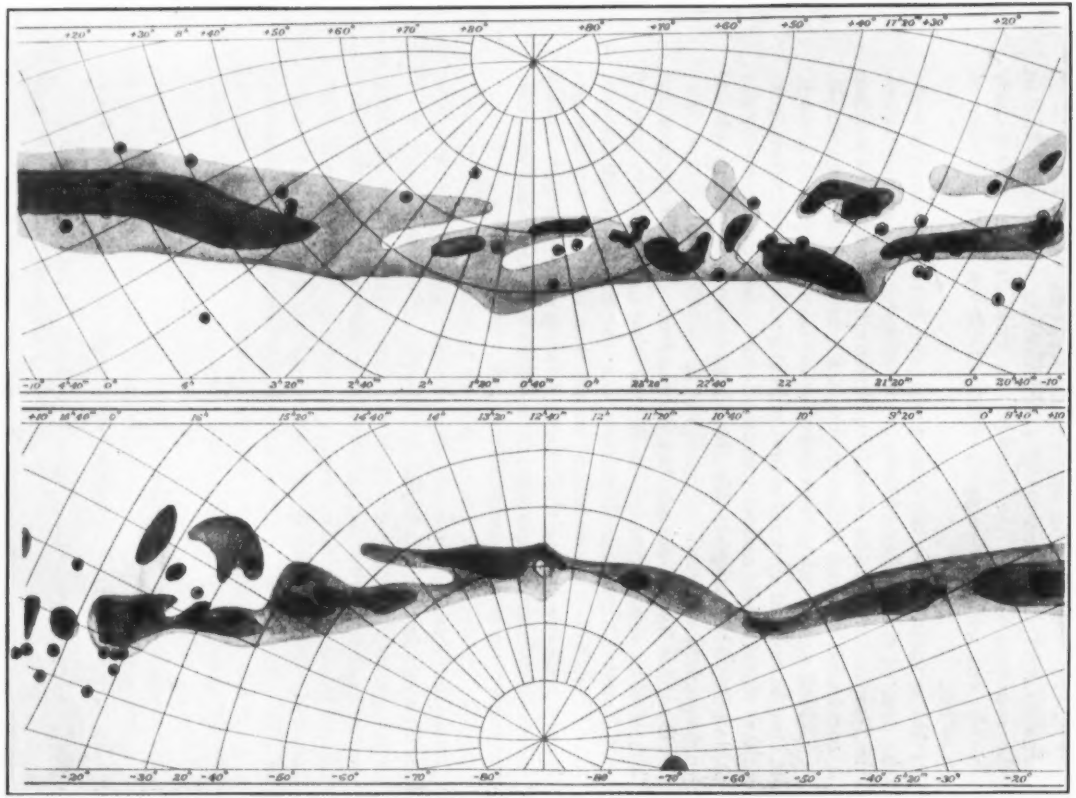

Fig. 2 (above).—Northern Milky Way.

Fig. 3 (below).—Southern Milky Way.

In the branch going north from Cygnus, we find very high negative velocities averaging approximately −40 km., while in the southern branch the presence of two streams is distinctly visible, one with an average velocity of −3 km., and the other of −38 km.

Were it not for the two distinct streams in this southern branch, the present change from highly positive to highly negative velocities from one side of the celestial sphere to the other, might indicate a considerable solar motion with respect to the pseudo-cepheids.

Added to the two streams of the southern Milky Way branch, it may be noticed that the true Cepheids, which are not Antalgols, follow this branch almost exclusively, as can be seen on figures 2 and 3. This suggests for the Cepheids an important outside cosmogonical cause.

On these figures are plotted all the true Cepheids with period longer than one day as given in the table published on pages 6 and 7, vol. IX., of the Dominion Observatory Publications.

Although the data on which this article is based are very meagre, it must be borne in mind that the stars investigated are considerably more distant than the usual stars for which accurate radial velocities have been investigated statistically.

Dominion Observatory,
Ottawa, January 5, 1927.

RECENT DEVELOPMENTS OF COSMICAL PHYSICS.[1]

By J. H. Jeans

Until recent years astronomy was concerned almost entirely with the sun, moon, and planets; the stars were mere points of light so inconceivably remote as to be of only minor interest. To-day Urania has wearied of the speck of dust we call the solar system, and claims the whole universe for her playground; the astronomer's interest centres almost exclusively on the stars. The dynamical astronomer, for example, having lost interest in the motions of the planets and their satellites, studies the arrangement and motions of the stars in the hope of discovering the general plan at least of the architecture and mechanism of the universe; for him the whole universe is a single dynamical system formed of innumerable particles—the stars—each of which attracts each other according to the universal law of gravitation.

The physical astronomer finds a different interest in the stars. For him each separate star is a complete physical system: it is a crucible in which matter is subjected to temperatures and pressures far beyond any available to the terrestrial physicist. From a study of the radiation emitted by the stars, the physical astronomer tries to unravel their physical structure, to discover how they generate their energy, and by what mechanism this energy is transmitted to their surfaces and discharged into space as radiation. In this way he may perchance happen upon properties of matter which have eluded the terrestrial physicist owing to the small range of physical conditions at his command. If the simile may be pardoned, on the plea that it is at least true to scale, the animalculæ which inhabit a raindrop may learn something of the properties of water by manipulating the particles of the raindrop with their puny strength, but they may also learn something by watching the uncontrollable fall of torrents over Niagara. The primary study of the physical astronomer is precisely this external fall of

[1]A lecture delivered at University College, London, on November 9, 1926. Printed in *Nature*, December 4, 1926.

torrents over Niagara; his ultimate aim is to weld cosmical physics on to terrestrial physics so as to form one all-embracing science. Only when this has been done will it be possible to understand the main trend of events in the physical universe.

The Interpretation of Stellar Spectra.

There is only one method available to this end, namely, a study of the radiation emitted by different stars. Apart from unscientific speculations, physical astronomy may be said to have come to birth in 1863, when Huggins attached a spectroscope to a telescope and found that certain lines in the spectra of the stars were identical with lines emitted in the laboratory by the known chemical elements. The early stellar spectroscopists believed that they were investigating 'the chemistry of the stars' although we know now that they were merely opening up a fundamental problem of the physics of the stars. The spectrum of Sirius, for example, was found to exhibit hydrogen lines very strongly and calcium lines very weakly; in the solar spectrum the relative strength of these two sets of lines was reversed, calcium being strong and hydrogen weak. They concluded that hydrogen was specially prominent in the constitution of Sirius and calcium in that of the sun. Believing that Sirius must one day develop into a star similar to our sun, they conjectured that its substance must gradually change from hydrogen into calcium and other more complex elements, thus finding support for the long-established hypothesis that the more complex elements were formed by gradual evolution out of the simplest.

The true interpretation of these early observations, as the investigations of Saha, R. H. Fowler and Milne have abundantly proved, is merely that the surface of Sirius is at a temperature at which hydrogen is specially active in emitting and absorbing radiation, while the sun's surface is at a lower temperature at which hydrogen is comparatively inert, calcium, iron, etc., having become active in its place. Just as the laboratory physicist can produce different spectra from the same vacuum-tube by varying the mode and conditions of excitation, so Nature produces different spectra from the same stellar material by varying its temperature.

Clearly this circumstance robs stellar spectra of all direct evolutionary significance. The spectra of the stars merely tell us their present surface temperatures, so that even if we could arrange the stars in order of age, a comparison of their spectra would only show whether their surfaces were becoming hotter or cooler; it would give no information as to chemical changes occurring in their substance.

The Sizes of the Stars.

The knowledge of a star's surface temperature nevertheless opens the door to further valuable knowledge. The hotter a surface is, the more energetically it radiates heat, and from a knowledge of a star's surface temperature it is easy to calculate its radiation per square inch of surface—the sun, for example, radiates approximately 560,000 calories a minute, which is about the energy output of a 50 horse-power engine, from each square inch of its surface. The hottest stars of all probably radiate at least a thousand times as much per square inch of surface.

In this way we can estimate a star's radiation per square inch of its surface. We can also estimate the radiation from its whole surface; this can be calculated at once from its distance and apparent brightness. Simple division gives the area of the star's surface, and hence its radius and volume. Calculated stellar radii range from about 300 times the sun's radius for Betelgeux to about 0.03 times the sun's radius for the companion of Sirius.

As is well known, the diameters of certain stars have recently been observed directly with the Michelson interferometer, and the measured values agree almost perfectly with those calculated in the simple way just explained. The interferometer method is only available for the largest stars, but at the extreme other end of the scale the theory of relativity has come to the rescue. The shift of spectral lines toward the red, which Einstein predicted to be a necessary consequence of the theory of relativity, has been observed in the light received from the companion of Sirius, and its amount corresponds exactly to the radius calculated for the star in the way just explained. So much of a sensational kind has been written about the observational measurements of the diameters of Betel-

geux and of the companion to Sirius, that it may be well to remember that, while the *methods* were novel and of the greatest interest and importance, the *results* were precisely those that were generally expected, and such as a simple arithmetical calculation showed to be practically inevitable. Indeed, this calculation could only have failed in one way. It is based on the assumption that the surfaces of the stars emit their full temperature-radiation like the surface of the sun. If the stars had been transparent bodies like the planetary nebulæ, or solid bodies like the moon, this assumption would have been false, and the observations would have revealed its falsity.

Our gain of positive knowledge from these observations is that Betelgeux and the companion to Sirius are neither transparent nor solid bodies, but full radiators like the sun. Moreover, as the three stars just mentioned are about as different as any three stars possibly could be, representing approximately the two extreme ends and the middle of the scale in almost any ordered arrangement we please to make, it seems reasonable to suppose that all stars are full radiators and so, as regards their mechanism of radiation, are essentially similar structures.

The Physical State of Stellar Interiors.

What, then, is this mechanism of radiation? And what, as a preliminary question, is the physical state of stellar matter? In the early days of spectroscopy it was commonly supposed, from a faulty analogy with laboratory experiments, that a hot gas always gave a line spectrum, and that a continuous spectrum, such as is exhibited by the stars, could be emitted only by a solid or a liquid body. It is now generally conceded that this view was erroneous, and it is recognised that the continuous spectrum of a star merely indicates that the star is not transparent, thus leaving the question of stellar structure almost entirely open.

The view of stellar structure now universally accepted is that stars are formed of matter which, as a consequence of its high temperature, is to a very large extent broken up into its constituent electrons and nuclei, these all moving about independently like the molecules of a gas. The electrostatic attractions which in

more peaceful surroundings would rapidly unite the wandering nuclei and electrons into complete atoms and molecules, are powerless in the general whirl of rapidly moving projectiles and in face of the shattering blows of the quanta of high-frequency radiation which the high temperatures of the stellar interiors generate. When I first put forward this view in 1917 (Bakerian Lecture, *Phil. Trans.*, 218, p. 209), I thought it was entirely novel, but I have since found that in 1644 Descartes had conjectured that the sun and fixed stars were made of matter "which possesses such violence of agitation that, impinging upon other bodies, it gets divided into indefinitely minute particles." My own suggestion was not conjecture, being based on incontrovertible scientific grounds. In 1907 Emden had published calculations ("Gas Kugeln," p. 96) on the interior states of the sun and stars, in which he assumed the stars to be masses of gas resting in an equilibrium similar to that of the lower strata of the earth's atmosphere—the so-called 'adiabatic' equilibrium in which there are assumed always to be sufficient currents to keep the constituent gases thoroughly mixed by a process of stirring. On this supposition he found that if the sun were composed of air or other diatomic gas of equal molecular weight, its central temperature would be 455 million degrees, while if it consisted of hydrogen, or other diatomic gas of molecular weight 2, its central temperature would be 31.5 million degrees. These temperatures are so high that no atom or molecule could survice them; at 31.5 million degrees the quantum of radiation has energy 2.1×10^{-8} ergs, which is sufficient to move an electron through a potential difference of 13,500 volts. Even with such quanta flying about, the atomic nuclei are still safe, far higher than stellar temperatures being needed to dissociate these into their constituent electrical charges, but the electrons must of necessity nearly all be torn off atoms of moderate atomic weight and the nuclei left almost or entirely bare.

To a first rough approximation we may regard stellar matter, at any rate in the star's hot central regions, as consisting of a mixture of bare nuclei and free electrons. Passing outwards towards the star's surface, the temperature falls, and we come to atoms which are more and more fully formed, until finally, close to the surface, we meet atoms which are completely formed except

perhaps for one or two of their outermost electrons. In the surfaces of the coolest stars of all, we even find complete molecules, as, for example, the molecules of titanium oxide and magnesium hydride, which appear in the spectra of certain classes of stars.

The Mechanism of Stellar Interiors.

The mixture of free electrons and bare nuclei or imperfectly formed atoms will behave like a mixture of monatomic gases. In completely broken-up hydrogen, each hydrogen molecule gives rise to four flying units—two protons and two free electrons—so that the effective molecular weight of the mixture will be 0.5. The corresponding figure for helium is 1.33, for calcium 1.90, for iron 2.07, and for lead 2.50, but since atoms of lead would not be completely broken up at stellar temperatures, the actual value for stellar lead would be somewhat higher. If we momentarily adopt 2 as a mean molecular weight of stellar matter, we find that Emden's calculations give 31.5 million degrees for the central temperature of the sun if formed of hydrogen molecules (mol. wt. 2). Various adjustments must be made in this figure, but they are of comparatively minor importance, and Emden's original figure of 31.5 million degrees is probably not very far from the actual temperature of the sun's centre. Indeed, Russell has recently suggested that the great majority of stars have central temperatures fairly close to 32 million degrees (Nature, Aug. 8, 1925).

One of the necessary adjustments arises from Emden's calulations having neglected the pressure of radiation in stellar interiors.[1] At 31.5 million degrees the pressure of radiation is about 2500 million atmospheres. Huge though this is in comparison

[1] I first directed attention to this in reviewing Emden's book (*Astrophys. Jour.*, 30, 1909), p. 72, and gave a reasonably accurate estimate of the ratio of this pressure to ordinary gas-pressure in stellar interiors in 1917 (Bakerian Lecture, May 17, 1917, p. 209). Some months previously Eddington had given an estimate which made this ratio some hundreds of times too large. He corrected this at the earliest possible opportunity (*Mon. Not. R.A.S.*, June 1917), but not in time to overtake sensational statements, still occasionally encountered, that pressure of radiation is of predominant importance in the dynamics of stellar interiors.

with terrestrial pressures, it is only some five per cent. of the ordinary gas-pressure of the broken-up atoms and electrons at the sun's centre. We could allow for its dynamical effects by decreasing our assumed mean molecular weight by 5 per cent., but this mean molecular weight is not in any case known to within 5 per cent. In exceptionally massive stars, the pressure of radiation assumes somewhat greater importance. For example, at the centre of a star of some ten times the sun's mass, radiation pressure is about equal to gas-pressure. To allow for its effects in this case we should have to suppose the assumed mean molecular weight halved—reduced perhaps from 2 to 1. In every case we shall get a true picture of stellar structure if we think of the layers of stellar matter as held up against gravitation by the incessant impact of a certain number of atomic nuclei or partially stripped atoms, the 'molecular weight' of which is practically the same as that of the corresponding complete atoms, together with a far greater number of free electrons of standard 'molecular weight' 0.00055, and a rather small number of 'molecules' of radiation the molecular weight of which is negligibly small. The combined impacts of these three types of projectiles prevent the star from falling in under its own gravitational attraction.

This gives us, I think, the best snapshot picture of a star's structure. The corresponding picture of its mechanism is obtained by thinking of the nuclei as α-ray particles, of the free electrons as β-ray particles, and of the radiation as γ-rays (although in most stars the main bulk of the radiation has the wave-length of X-rays); and, precisely as in laboratory work, the β-rays are more penetrating than the α-rays, and the γ-rays are more penetrating than either.

The Transport of Energy inside a Star

In ordinary kinetic theory of gases, conduction of heat is studied by regarding the molecules of the gas as carriers of energy; each molecule has a carrying power which is jointly proportional to its heat energy, its velocity and its free-path. In the interior of a star there are, as we have seen, three distinct types of carriers—the nuclei (or atoms), the free electrons, and the radiation. We

can compare the relative carrying capacities of these three types of carriers by multiplying up the energy, velocity, and free-path of each.

The nuclei and the free electrons have, of course, quite definite free-paths. The same is true of the radiation if this is regarded as consisting of discrete quanta; when a quantum is emitted a free-path begins, and when it is re-absorbed the free-path ends. Whether we think in terms of undulatory theory or quanta, we may suppose that a beam of radiation is reduced in intensity by a factor $e^{-k\rho x}$ on passing through a thickness x of matter of density ρ, where k is the 'coefficient of opacity' of the matter. By comparison with the kinetic theory formula $e^{-x/\lambda}$ for the reduction in strength of a shower of moving molecules, we see that the 'free-path' of the radiation must be taken to be $1/k_\rho$. When we use this value for the free-path of radiation and calculate carrying capacities in the way already explained, the carrying capacity of both nuclei and electrons is found to be insignificant in comparison with that of the radiation. The nuclei and electrons may have the greater amount of energy to carry, but the distance over which they carry it, their free-path, is far less than that of the radiation, and their speed of transport is also less, since radiation transports energy with the velocity of light. In this way it comes about that practically the whole transport of energy from the interior of a star to its surface is by the vehicle of radiation.

This general principle was first clearly stated by Sampson in 1894 (*Mem. R.A.S.*, 51, p. 123), but his detailed applications were vitiated by his using an erroneous law of radiation. Twelve years later, Schwarzschild independently advanced the same idea (*Gött. Nach.*, 1906, p. 41); he showed how the temperature of any element of a star's interior must be determined by the condition that it received just as much radiation as it emitted, and gave accurate equations of radiative equilibrium which have formed the basis of every subsequent discussion of the problem.

The Configurations of a Star in Equilibrium

As a consequence of radiation completely outstripping the material carriers in the transport of energy to the star's surface,

the build of a star is entirely determined by the values of k, the coefficient of opacity in its interior. If this coefficient is everywhere zero, the star is entirely transparent, and so cannot retain any heat; we now have a star of zero temperature and therefore of infinite extent. If, on the other hand, the coefficient of opacity is everywhere infinite, the star is completely opaque, so that all radiation accumulates where it is generated until the star's temperature becomes infinite, and we have a star of infinite temperature but of infinitesimal radius. It is, of course, the intermediate values which are of practical interest, but the two extreme cases just mentioned show how the whole build of a star depends on the value of the opacity coefficient k. So much is this the case that all attempts to investigate the build of stars before the value of this coefficient was known can only be regarded as speculation.

The first attempt to evaluate it theoretically by Eddington in 1922 (*Mon. Not. R.A.S.*, 83, p. 32) proved unsuccessful and was withdrawn. In the next year Kramers (*Phil. Mag.*, 46, p. 836) put forward the theory of opacity which has now gained general acceptance. Using the value of the opacity coefficient given by this theory, it is possible to determine the complete build of a star having any given mass and any given rate of generation of energy. In this way I have shown (*Mon. Not. R.A.S.*, 85, pp. 196 and 394) that a star of given mass can rest in equilibrium with any radius from zero to infinity, different radii corresponding to different rates of generation of energy from zero to infinity by the star. A star adjusts its radius to suit its rate of generation of energy, and in so doing fixes its surface temperature and spectral type. If a star's rate of generation of energy were suddenly to change, the star would expand or contract until it had assumed the radius and temperature suited to its new rate of generation of energy. Contrary to common belief, an increase in a star's rate of generation of energy causes it to contract its radius and increase its temperature, while a slackening in its generation of energy is found to result in expansion and cooling. Thus we see the giant red stars such as Betelgeux do not owe their immense size to their radiating so much energy, but to their radiating so little; indeed, comparatively compact stars such as Plaskett's star and V Puppis are radiating far more in proportion to their masses. The general

theoretical principle can be verified by the examination of pairs of stars of approximately equal mass, as for example the two pairs in the following table. The surface temperatures are here deduced directly from the observed spectra, the radii then being calculated in the way already explained.

Star.	Mass (in terms of sun).	Generation of energy per gram (ergs per second).	Observed temperature.	Radius (in terms of sun).
Sun	1.00	1.9	5750	1.00
α Cent. B	0.97	1.4	3700	2.03
Procyon	1.13	10.2	8300	1.17
α Cent. A	1.14	2.3	5000	1.56

Stellar Evolution.

There is not likely to be any abrupt change in the rate of generation of energy of an actual star. There will be a slow secular decrease, but this will be associated with a slow secular decrease of the star's mass resulting from its continual emission of radiation. For example, the 560,000 calories of radiation which stream out every minute from each square inch of the sun's surface have a mass of 2.5×10^{-8} gm., whence it is readily calculated that the sun's mass must diminish by 250 million tons every minute. After millions of millions of years this rate of wastage produces an effect even on the gigantic mass of the sun. To trace the changes in the radius and temperature of an actual star we must study the sequence of configurations assumed in turn as the mass and the rate of generation of energy change together. In this way I have found (*Mon. Not. R.A.S.*, January 1925) that a normal star would first decrease in size and get hotter, but would ultimately expand and get cooler again. This result provides a simple dynamical interpretation of the sequence of 'ascending and descending temperatures' which was first suggested by Lockyer, and formed the outstanding feature of Russell's 1913 theory of stellar evolution—although our physical interpretation is very different from that suggested by Russell.

The Atomic Weight of Stellar Matter

In the simplest case, in which energy is generated uniformly throughout a star's mass, the surface temperature T assumed by a star of mass M and of given luminosity (or rate of generation of energy) is given by the equation—

$$\text{Star's luminosity} = C\left(\frac{N^2}{A}\right)^{-0.8} T^{6.8}\mu^{6.8} f(M).$$

Here C is a known constant, N and A are the atomic number and atomic weight of the stellar atoms, and μ the effective molecular weight (about 2) of the broken-up stellar material; T is the temperature of the star's surface and $f(M)$ is a quantity I have calculated and tabulated, which depends only on the star's mass (*Mon. Not. R.A.S.*, 85, p. 395).

The quantity N^2/A necessarily occurs in the foregoing formula, because the coefficient of opacity, by which the star's whole structure is determined, is proportional to N^2/A. If a Maxwell demon could cut every atomic nucleus in a piece of matter into two equal halves, he would halve both N and A and so also N^2/A, with the result that the substance would become twice as transparent as before. This shows that a large clot of matter in the form of a massive nucleus is far more effective in absorbing X-radiation than a large number of small clots of equal total mass. It is for this reason that the physicist and surgeon both select lead as the material with which to screen their X-ray apparatus; a ton of lead is far more effective in stopping unwanted X-rays than a ton of wood or of iron. If we knew the strength of an X-ray apparatus, and the total weight of shielding material round it, we could form a very fair estimate of the atomic weight of the shielding material by measuring the amount of X-radiation which escaped through it.

A very similar method may be used to determine the atomic weight of the atoms of which the stars are composed. A star is in effect nothing but a huge X-ray apparatus. We know the total mass of many stars, and we can readily calculate the rate at which they are generating X-rays—it is merely the rate at which they are radiating energy away into space. If we could shut our Maxwell demon inside a star and make him cut each atomic nucleus in half,

keeping the star's mass and rate of generation unaltered, we should halve the coefficient of opacity of the star. This would necessitate a change in the star's build: in actual fact its radius would increase fourfold while its surface temperature would be halved. We could follow the progress of the demon's work by watching the changes in the surface temperature of the star. Hence from the observed surface temperature of any star the mass and luminosity of which are known, it must be possible to estimate the atomic weight of the atoms of which the star is composed. The formula given above provides the means.

I ought perhaps to mention in passing that Eddington and others have approached this question from the other end, assigning conjectural values to N^2/A from our knowledge of the elements which occur in the atmospheres of the sun and stars. Such a course appears to be very risky. A star's spectrum gives no indication of the selection of elements which occur in its interior; and there is at least an *a priori* possibility that the elements occurring there may be entirely different from those which appear in its surface; consider into what errors an extra-terrestrial observer might be led if he assumed that the earth contained no chemical elements beyond those appearing in its atmosphere.

When, however, the risk has been taken, and such values assigned to N^2/A, all the quantities which occur in the luminosity formula are known, and the only question which remains is whether the values calculated for the luminosity agree with those observed through the telescope. They do not.

It is clear that the value of N^2/A must be adjusted until agreement is obtained, and this amounts to precisely the same thing as determining N^2/A, directly and at once, from the luminosity formula. On doing this for a series of stars, I have found (*Mon. Not. R.A.S.*, June 1926) that two very significant facts emerge. First, most of the values so determined prove to be higher than the value for uranium, the heaviest element known on earth. Second, the different values of N^2/A show an ordered arrangement, the youngest stars generally giving the highest values for N^2/A, and this value falling as we pass to older stars.

The second of these results has far-reaching implications. Contrary to the views of the early spectroscopists, and contrary

to what is still probably the prevalent belief, it now looks as though the atoms in a star become simpler as the star grows older; evolution appears to be from complex to simple, and not, as in biology, from simple to complex. There is at present no direct experimental evidence bearing on this question except that provided by radioactivity, where evolution is certainly from complex to simple, atoms of lower atomic weight being continually produced by the disappearance of atoms of higher atomic weight.

The evidence of physical astronomy, pointing to an evolution of matter in the same direction, suggests that the main evolution of matter in the universe may be of the same type as, but a generalisation of, the radioactive processes as they occur on earth. The evidence so far given has been based entirely on Kramers' theory of opacity for X-radiation. This theory has been found to agree very well with the observed absorption in the laboratory of radiation of about the wave-length which occurs in stellar interiors, while its theoretical basis has been discussed fully and critically by Eddington, Milne, and others, who have been unable to suggest any substantial alteration. Still, if the evidence from Kramers' formula were the only evidence available, our conclusions would be open to the charge of resting, if not on a slight, at least on a single, foundation. But there is plenty of further evidence, as we shall now see.

Distribution of Chemical Elements in a Star.

A star necessarily arranges itself so that there is a great concentration of matter near its centre. This is primarily a consequence of the inverse square law of gravitation, although the opacity law is involved also to some extent. With Kramers' formula for the opacity the arrangement is such that the central density is 100 or more times the mean density, while at least some 90 or 95 per cent. of the star's total mass is concentrated in a sphere of half the radius, and so of only one-eighth the volume, of the star. But the degree of central condensation is rather insensitive to changes in the opacity formula, and any reasonable formula would still give very high central condensation. A strict mathematical argument based on this circumstance (*Mon. Not. R.A.S.*, June

1926, p. 561) enables us to rule out the poss bility of convection currents stirring up a star's interior in the way in which boiling water is stirred up in a kettle. Convection occurs in a kettle because the hot water at the bottom is of lower density than the cool water at the top; it is absent in a star because the hot matter near the centre, notwithstanding its intense heat, is still far, far denser than the cool matter near the surface. Thus, the mixture of matter in a star's interior is not analogous to that in the earth's lower atmosphere, where the constituent gases are kept thoroughly mixed by winds and storms, but rather to a serene upper atmosphere in which the lightest elements float to the top while the heaviest sink downwards under gravity.

Such considerations as these suggest at once that the elements which indicate their presence in the spectra of the outermost layers of the sun and stars are only the very lightest of the series of elements existing in the star. It is natural that the earth, formed originally out of the sun's outer layers, should contain precisely the same chemical elements as these outer layers, but it now appears that there ought to be heavier elements inside. The calculation which assigns to stellar matter atomic numbers higher than that of uranium no longer looks suspicious or paradoxical; it begins to look natural, and indeed almost inevitable.

The Generation of Energy in a Star.

Further evidence that the atomic weights of stellar atoms are higher than those of any known terrestrial atoms may be obtained by considering the rate of generation of energy inside a star. The sun radiates energy at about 2 ergs per second for each gram of its mass, and so must generate energy at this rate in its interior. To the best of our knowledge it has generated and radiated at this, or a greater, rate for some millions of millions of years. Could the sun have any such radiating capacity if its interior were formed of the common terrestrial elements, calcium, iron, silicon, etc.?

One's first impulse is to say, No. Even if the sun were built of pure uranium, its radiating power would be only about one-half of that observed, and would only last for a minute fraction of what is believed to have been the sun's life. A sun of pure radium would

radiate more than enough for the moment, but its life would be limited to a few thousand years. No possible combination of terrestrial elements can give the combination of high radiation and of staying power which is observed in the sun and stars.

We must, however, remember that stellar interiors are at pressures and temperatures which are quite unattainable in our laboratories. We are led to wonder whether our terrestrial elements would behave quite differently if they were exposed to stellar conditions. Is it possible, for example, that the sun's interior is formed of ordinary terrestrial elements, which owe their high generation of energy merely to their high temperatures and pressures?

A general survey of astronomy throws a good deal of light on this question. We find immediately that the stars which radiate most energetically (per unit mass) are not, broadly speaking, the hottest stars, and neither are they the densest. Some of of the hottest and densest stars are entirely put to shame in the matter of radiation by very cool stars of low density such as Antares and Betelgeux. If we arrange the stars in order of radiation per unit mass, we shall find that we have arranged them neither in order of temperature nor of density, but very approximately in order of age; the youngest stars radiate most energetically, regardless of their interior temperatures and density; the older stars appear to be tired out.

The general tendency is shown in the following table:

Star.	Generation of energy (ergs per gram).	Central temperature.	Central density.	Age.
Plaskett's Star	1000	500,000,000	Very great	
V Puppis	640	300,000,000	More than 1,000	Less than
Antares	320	1,000,000	0.005	10^{12} yr.
Capella A	50	8,000,000	0.5	Less than 10^{12} yr.
Sirius	21	150,000,000	1,000	10^{12} yr.
Sun	1.88	70,000,000	300	7×10^{12} yr.
α Cent. B	1.39	15,000,000	10	7×10^{12} yr.
Kruger 60 B	0.02	70,000,000	30,000	Very old.
Sirius B	0.003	Unknown	More than 53,000	Unknown

If it is asked whether densities so high as these can really exist at the centres of the stars, the answer is provided by the companion to Sirius (Sirius B). Direct observation has shown that the *mean* density of this star is about 53,000, and the central density must of course be higher. Incidentally, as Eddington has remarked, this provides striking confirmation of our view that stellar matter consists of atoms broken up into their fundamental constituents. It is impossible to compress matter formed of complete atoms of radii 10^{-8} cm. or more to anything approaching these high densities, but there is no difficulty as regards minute nuclei and electrons of radii of the order of 10^{-13} cm.

It has to be admitted that many of the entries in the table are highly conjectural, and few can claim any great accuracy. But while many astronomers may prefer different values for individual entries in the table, I doubt is any would seriously challenge the general contention that a star's energy-generating capacity depends primarily on its age, and not, at any rate primarily, on its central temperature or density.

No doubt exceptions to the general rule can be found. An extreme example is provided by the earth and sun; the matter of which these two bodies are formed must be of the same ultimate age, yet they radiate at very different rates per unit mass. This is readily explained if we suppose the heavy atoms from which the sun's energy originates to have sunk deep into its interior, and so not to have entered into the composition of the earth and planets: a similar explanation will account for the different radiating capacities of the components of binary systems. But these exceptions result from special conditions prevailing in special cases; they do not affect the general law that a star's generation of energy is not determined by either its density or its temperature.

The accompanying table shows that the law is well supported by observational astronomy; it can also be reached from a theoretical study of the actual process of generation of energy in a star. A mass of evidence, mostly dynamical, indicates that the stars must have existed for millions of millions of years. To take one example, newly formed binary stars have circular, or nearly circular, orbits; this is a consequence of the manner of their formation. Every gravitational pull on a circular orbit tends to make the orbit more

elliptical, so that the older a binary star is, the more elliptical its orbit ought to be. This is actually found to be the case. But from our general knowledge of the number and masses of the stars wandering about in space, we can estimate the rates at which the ellipticities of the orbits of binary stars ought to increase, and this in turn makes it possible to estimate the ages of actual stars. It is a mere problem of dynamics, and the answer comes out in millions of millions of years.

We can now estimate the total amount of radiation which must have been emitted by particular stars in the millions of millions of years they have existed; and, except in the case of the youngest stars of all, the total mass of this radiation is found to be far greater than the present mass of the star. We obtain the mass of the star at its birth by adding the mass of all this radiation to that of the matter now remaining in the star. Thus its mass at birth must have been far greater than now. But, as a star's mass at any instant consists almost wholly of the mass of the matter of which it is composed, we see that the greater part of the matter contained in the original star has ceased to exist as matter; it has been annihilated and transformed into radiation which the star has radiated away into space. So far back as 1904 (NATURE, 70, p. 101) I put out the suggestion that energy might be created by the annihilation of matter; it now appears that this process must in actual truth be the source of the energy emitted by the sun and stars. Throughout a star's interior, electrons and protons must at intervals fall into one another and mutually destroy one another, the energy of their fall being set free as radiation.

The energy of this fall is enormous, being sufficient to set both the masses involved into motion with a velocity of 0.866 times that of light. In no other way can a given mass of matter be made to yield energy of amount comparable with this; for example, whereas the ordinary combustion of a ton of coal provides energy enough to drive an express locomotive for an hour, the annihilation of a ton of coal would provide enough energy for all the heating, lighting, power, and transport in Great Britain for a century.

Each proton or atom, as it is annihilated, makes a splash of radiant energy which travels through the star until, after innumerable absorptions and re-emissions, it reaches the star's surface

and wanders off into space. Each splash is similar to the splashes produced by radio-active material in the spinthariscope, except for being many thousands of times more powerful. The great energy of the splashes is to some extent counterbalanced by their rarity. In the sun, for example, only about one atom in every 10^{17} annihilates itself each hour. A cubic centimetre of the sun's mass contains, let us say, 10^{22} atoms, and of these about 100,000 are annihilated every hour. The energy produced in a cubic centimetre of the sun's mass is thus not very great, averaging about 9400 ergs or 0.00022 calories per hour; the enormous flow of energy from the sun's surface results from the fact that all the energy produced in a cone 433,000 miles in depth has to stream out through the mouth of this cone.

Such, in brief, is the mechanism by which stellar energy is generated. The question immediately before us is whether this generation of energy proceeds more merrily, whether the electron and protons fall into one another more frequently, when the stellar matter is in a state of high temperature and high density.

It is a matter of direct observation that ordinary radioactive processes cannot be either inhibited or intensified by such temperatures as are available in the laboratory; the quantum theory provides the reason. Einstein has shown how a sub-atomic generation of radiation can occur in either of two ways, spontaneously or through the stimulus of incident radiation, and it is easy to calculate the temperature at which the second process becomes operative. It is found that the quantum of radiation at this temperature must have energy equal to the energy set free by the sub-atomic change in question. The temperature necessary to expedite the disintegration of uranium is in this way found to be of the order of 120,000 million degrees, and it at once becomes clear why warming up uranium in the laboratory cannot speed up its disintegration. A similar calculation shows that the temperature necessary to influence the rate of sub-atomic annihilation of matter is of the order of 7,500,000 million degrees. It may be argued that a lower temperature, although not adequate to bring about the actual annihilation of matter, might set up sub-atomic processes of adequate intensity. This is true as regards a star's momentary radiation, but such processes cannot provide an adequate duration

for the radiation. All processes which are affected by temperatures of less than about 7,500,000 million degrees leave the total number of electrons and the total number of protons in a star unaltered, whereas the whole evidence of astronomy is that the number of electrons and protons in a star must continually decrease.

With this figure before us, it is clear that the comparatively feeble stellar temperatures of less than a thousand million degrees must be quite inoperative in regard to the main generation of stellar energy; indeed the heat of the hottest of stellar interiors can have no more influence on the rate of annihilation of matter than a warm summer's day has on the rate of disintegration of uranium. Thus it seems abundantly clear that what is annihilating the matter of the stars is neither heat nor cold, neither high density nor low, but merely the passage of time.

These considerations notwithstanding, it has been suggested by Russell (NATURE, Aug. 8, 1925), whose ideas were afterwards adopted by Eddington (NATURE May 1, 1926), that the annihiilation of matter (which they agree to be the ultimate source of stellar radiation) may be produced by the raising of ordinary matter to a critical temperature of some 30 or 40 million degrees. Russell suggests that matter is, broadly speaking, inert until it reaches this critical temperature, when an unlimited transformation of matter into radiation suddenly takes place.

In addition to running foul of the physical principles just explained, this suggestion encounters the difficulty that the generation of energy it provides would not only be unlimited but also illimitable; when once it began there would be no stopping it. The proposal of Russell and Eddington would, in effect, make matter thermodynamically unstable at stellar temperatures by endowing it with the properties of an explosive at its flash-point. When once stellar matter reached its flash-point, its resulting annihilation would generate so much heat that the adjacent matter would also in turn be raised to the flash-point, and the whole star would almost instantaneously explode into radiation. The sky would show no steady star-light, but merely a succession of apparitions of novæ of the most terrifying kind, as the various stars reached their flash-points and 'popped off' in turn. In spite of the astronomical eminence of its father and stepfather, I, for one.

find it impossible to accept a hypothesis which is not only contrary to the general principles of physics, but also against which the very stars fight in their courses.

A general mathematical discussion of the stability problem shows that a star built of matter the rate of generation of energy of which is absolutely unaffected by changes of temperature and density, will be dynamically stable. But such a star, although stable, has not much stability to spare. If we change the properties of our stellar matter in the sense of making an increase of temperature increase the rate of generation of energy, we lessen the already small margin of stability. Any substantial step in this direction would render the star dynamically unstable.

Combining this purely dynamical result with the physical principles already explained, it becomes clear that we may, to a good first approximation at least, suppose that an increase in the temperature of stellar matter produces no increase at all in its rate of generation of energy.

Stellar radiation must either originate in types of matter known to us on earth or else in other and unknown types. When once it is accepted that high temperature and density can do nothing to accelerate the generation of radiation by ordinary matter, it becomes clear that stellar radiation cannot originate in types of matter known to us on earth. Other types of matter must exist and, unless physics and chemistry have gone very far astray in recent years, these other types can only be elements of higher atomic weight than uranium. The significance of the calculation which showed that stellar atomic weights are, in the main, higher than that of uranium now becomes apparent.

Recapitulation and Interpretation of Results.

We have now reached the conclusion, by three distinct paths, that the atomic weights of stellar atoms must in the main be higher than that of uranium:

(1) By direct calculations from Kramers' formula.

(2) From the consideration that the atoms near the centre of a star must be substantially heavier than those near its surface.

(3) From the consideration that atoms of atomic weight less

than uranium, no matter how much they were heated or compressed, could not provide the intense and lasting radiation emitted by the stars.

The atomic weights of stellar atoms are not only found to be higher than that of uranium, but also they vary systematically from star to star. In brief, the youngest stars are found to have the highest atomic weights, and with this clue all the pieces of the puzzle are found to fit together.

We have to suppose that matter in its earlier state consists of a mixture of elements of different atomic weights, those elements the atomic weights of which are highest having the greatest capacity for the spontaneous generation of radiation by annihilating themselves, and, in consequence, having the shortest lives. These elements will be the first to disappear as the star ages, their disappearance reducing not only the mean atomic weight in the star but also the mean rate of radiation per unit mass, since these heavy elements are the most energetic radiators. Just as, on the coast, the hardest rocks survive for longest the disintegrating action of the sea, so in a star the lightest elements survive for longest the disintegrating action of time, so that ultimately the star contains only the lightest elements of all and so has lost all radiating power. Our terrestrial elements have so little capacity for spontaneous transformation that they may properly be described as 'permanent'. Calculation shows that if they underwent any appreciable transformation in periods comparable with the life of a star (say 10^{13} years) the spontaneous generation of heat by the earth's mass would make the earth too hot for human habitation. The radioactive elements are of course an exception; they probably represent the last surviving vestiges of more vigorous primeval matter, and so form a bridge between the inert permanent elements and the heavier and shorter-lived elements of the stars.

An interesting question is whether the heavy atoms change into radiation instantaneously, or only through successive stages of transformation. Astronomical evidence makes it fairly certain that the most massive stars contain more atoms than our sun, there being a wider range in the weights of the stars than in the atomic weights of their atoms. As these stars must in time become

reduced to the mass of our sun, the process of evolution clearly calls for an actual annihilation of atoms; it is not enough to postulate a mere gradual decrease in the atomic weight of each atom until it ends as a permanent atom. Radioactivity suggests that this latter process may also occur, but the evidence of astronomy is that it is at best a subsidiary process.

The number of 'permanent' atoms in a massive star such as Antares or V Puppis cannot undergo any perceptible diminution in the next 10^{13} years, so that they must all survive in the final star of mass perhaps only a fiftieth of that of the present star. Thus some ninety-eight per cent. of the present masses of these stars must consist of non-permanent atoms. To put it in another way, the present mass of a star such as Antares or V Puppis must consist, as regards 98 per cent., of atoms which are destined to change into radiation, and as regards only 2 per cent. of atoms which cannot change into radiation. Clearly the primary matter of the universe must be of non-permanent type; our terrestrial atoms are a mere residue of non-transformable ashes. Like the animalculæ of the raindrop looking out on to Niagara, we discern that our physics and chemistry are only the fringes of far-reaching sciences; beyond the seashore we have explored in our laboratories lies the ocean the existence of which we are only just beginning to suspect.

We are thus led to picture the youngest stars as formed of matter practically all of which is unknown on earth, being of atomic weight higher than that of uranium. This possesses the capacity of annihilating itself spontaneously, the energy produced in the process being set free as radiation. Its rate of generation of energy, as estimated from the luminosities of the youngest stars, is of the order of 1000 ergs per gram per second. As the annihilation of 1 gram of matter produces 9×10^{20} ergs of energy, the matter must have a 'period of decay' of 9×10^{17} seconds, or about 30,000 million years. As the star ages, and only less transformable matter remains, the period of decay is correspondingly lengthened. The matter in the sun, radiating 2 ergs per gram per second, must have a period of decay of 15,000,000 million years. It is these periods of decay which determine the rates of evolution and length of life of the stars. Broadly speaking, a star lasts as long as the atoms

of which it is composed, and the lives of these atoms are constants of Nature.

We notice that the periods of decay of stellar atoms are long compared with the periods of ordinary radioactive decay, suggesting that the radioactive elements are mere transitory formations in the evolution of the elements.

The Critical Central Temperature.

A group of stars selected for having approximately equal masses —as, for example, the sun, Procyon, and the two components of α Centauri—might be expected *a priori* to have very different rates of generation of energy, with the result that the stars would have very different surface temperatures and also very different central temperatures. Indeed, on first approaching the question, the whole range of temperatures from zero to infinity would seem to be open for each of these quantities. Yet in actual fact the surface temperatures of the four stars mentioned, as also of all stars of the same mass, lie within the narrow range between 3700 and 8300 degrees; their central temperatures probably lie within the range from 15 to 100 million degrees. For stars of other masses the limits are different, and are substantially wider for stars of great mass. But the stars of any definite mass always show a definite upper limit of temperature, both for the surface temperature and for the central temperature. These limits are never exceeded, but the majority of stars of the particular mass in question seem to crowd towards them. The existence of one limit of course implies the existence of the other, and it seems likely that the limit to the central temperature is the more fundamental. Stars having the same mass as our sun never have central temperatures higher than 80 million degrees, while the majority have central temperatures not very far below 80 million degrees. For stars twenty times as massive as our sun, the corresponding limit is probably somewhere about 300 million degrees, while there are intermediate limits for stars of intermediate mass.

This is obviously one of the fundemental facts of physical astronomy: What does it mean? The normal event for a star like V Puppis, losing mass and capacity for generation of energy

together, would be a gradual shrinkage of size accompanied by a steady increase of central temperature. What is it that checks this normal course of evolution so soon as the central temperature touches 300 million degrees?

I have recently suggested that the upper limit of temperature for any star is smply that at which its central atoms begin to be stripped nearly or entirely bare of electrons. This is merely a matter of simple calculation, but we have to suppose the atoms at the star's centre to have the high atomic weights which other considerations, as we have seen, assign to them. For example, a temperature of 300 million degrees suffices to strip the last electrons off atoms of atomic weight 300 or more. The fall in the critical central temperature as a star gets older and less massive is, on this view, a direct consequence of the decrease in the atomic weight of the stellar material, which occurs as the heaviest atoms gradually annihilate themselves.

It remains to explain why this temperature constitutes an upper limit, why a star cannot go on getting hotter after its innermost atoms are stripped bare of electrons. So far as I can see, only one answer is possible: the stripping of the electrons from an atom must remove its power of annihilating itself, and so must inhibit its capacity for generating radiation. The central atoms of the star now act precisely like the governor of a steam engine, regulating the generation of energy so that the central temperature is kept close to the critical temperature. If the star begins to get too hot, the central atoms become stripped bare of electrons, and so leave off generating energy. The star then begins to cool off, and as it does so the atoms reform and resume their generation of energy, again heating up the star. The mechanism provides a perfect thermostat, and it is easily shown that its action is stable. As a star ages the heavier atoms at its centre are the first to be transformed into radiation and so to disappear; their place is taken by lighter atoms, and as a lower temperature suffices to strip these lighter atoms bare of electrons, the critical central temperature of the star falls.

An interesting confirmation of this hypothesis is provided by the components of newly formed binaries. These have the high energy-generating capacity per unit mass of young stars, associated

with the small mass appropriate to much older stars. Clearly the 'governor' action ought to be particularly active in checking the generation of energy in these stars, so that they ought to have central temperatures close up to the maximum for their mass. This is in actual fact found to be the case.

All the evidence at present available points to the annihilation of matter being a quantum phenomenon; possibly it represents nothing more than the spontaneous drop of an electron to a zero-quantum orbit. This would suggest an explanation of why bare nuclei and free electrons should be immune from annihilation, and hence why atoms stripped bare of electrons cannot generate energy.

Highly-penetrating Radiation.

If our earth exhibits only one end of the chain of chemical elements, where shall we look for the other end? Moving backwards along the evolutionary sequence we come to younger and yet younger stars, containing elements of higher and higher atomic weight. Passing beyond the stars altogether we come to the nebulæ; here we ought to find the elements of highest atomic weight of all, and the matter of greatest radiating capacity

Visually the nebulæ are extremely faint objects; their emission of visual radiation per unit mass is only about equal to that of our sun. There is, however, an essential difference between the radiation generated in the stars and that generated in the nebulæ. Radiation, when first generated, must have enormous penetrating power; the simultaneous annihilation of a single electron and proton produces radiation of wave-length only 1.3×10^{-13}cm. The high penetrating power of this short wave-length radiation, nevertheless, only suffices to carry it through a small fraction of the radius of a star, and successive absorptions and re-emissions soften it, by a sort of generalised Compton effect, until it finally emerges from the surface of the star as ordinary temperature radiation. The density of the nebulæ is, however, so much lower than that of the stars that similar radiation, when generated inside a nebula, passes almost unchecked directly into outer space. Here and there the radiation may devastate isolated atoms in its passage, ejecting a few million-volt electrons in the process, but the majority of it

will pass on unhindered until it meets a medium of substantial absorbing powers. Thus we should expect the atmospheres of the stars, sun, and earth, and even the solid body of the earth, to be under continual bombardment by highly-penetrating radiation of nebular origin.

Such radiation has been detected in the earth's atmosphere by Kolhörster, Millikan, and many others, who are satisfied that it is of extra-terrestrial origin. If it originated in the stars, the amount received would depend largely upon the position of the sun. As it does not, the radiation must originate in nebulæ or cosmic masses other than stars. Quite recently (NATURE, October 9, 1926), Kolhörster and von Salis have found that its intensity varies with the position of cosmic masses, in a way which indicates that the radiation is received largely from regions near the Milky Way, especially the regions of Andromeda and Hercules

I have calculated that the total amount of highly-penetrating radiation actually received is of the order of twice that which ought to be received from the Andromeda nebula alone (NATURE, December 12, 1925) if this consisted solely of matter of the same radiating power as the very youngest of the stars. Clearly the total amount of radiation which is observed to be received on earth is of the right order of magnitude; it is, moreover, so large that it is difficult to imagine any possible origin for it other than that just mentioned. Its penetrating power appears to be rather less than might have been expected if it originated in the actual annihilation of electrons and protons, but I do not think the difficulty, if it exists, is insuperable. Quite recently Rosseland (*Astro. Jour.*, May 1926) has suggested that bombardment by this radiation may be the cause of the observed bright lines in stellar spectra; I had previously (NATURE, December 12, 1925) suggested a similar origin for the luminosity of the irregular nebulæ.

There is a temptation to try to probe still further into the physics of the nebulæ, to try to understand the properties of matter in its earlier forms, perhaps even to get a glimpse of it in the actual process of creation. But to yield to this temptation would carry us too far into the realms of conjecture and speculation. So far the course of our argument has not depended on either conjecture or speculation. Where there has appeared at first to be a choice

of ways, all ways except one have proved on further examination to be prohibited either by observational knowledge or by well-established principles of physics or dynamics: there has never been any real choice. For this reason the conclusions we have reached, although certainly novel and perhaps unexpected, appear to me to be, in their main lines, inevitable; I can see no means of escape.

Life and the Universe.

A general survey of the results obtained by cosmical physics has suggested that terrestrial laboratory physics is a mere tail-end of the general science of physics. The primary physical process of the universe is the conversion of matter into radiation, a process which did not come within our terrestrial purview at all until 1904. The primary matter of the universe consists of highly dissociated atoms, a state of matter which, again, was not contemplated before 1917. The primary radiation of the universe is not visible light, but short-wave radiation of a hardness which would have seemed incredible at the beginning of the present century. Indeed, our whole knowledge of the really fundamental physical conditions of the universe in which we live is a growth of the last quarter of a century.

The simple explanation of this situation is to be found in the fact that life, naturally enough, begins its exploration of Nature by studying the conditions which immediately surround it; the study of the general conditions of the universe as a whole is a far more difficult task which life on this planet is only now approaching. Now the physical conditions under which life is possible form only a tiny fraction of the range of physical conditions which prevail in the universe as a whole. The very concept of life implies duration in time; there can be no life where the atoms change their make-up millions of times a second and no pair of atoms can ever become joined together. It also implies a certain mobility in space, and these two implications restrict life to the small range of physical conditions in which the liquid state is possible. Our survey of the universe has shown how small this range is in comparison with the range of the whole universe. Primeval matter must go on transforming itself into radiation for millions of millions of years to

produce an infinitesimal amount of the inert ash on which life can exist. Even then, this residue of ash must not be too hot or too cold, or life will be impossible. It is difficult to imagine life of any high order except on planets warmed by a sun, and even after a star has lived its life of millions of millions of years, the chance, so far as we can calculate it, is still about a hundred thousand to one against its being a sun surrounded by planets. In every respect—space, time, physical conditions—life is limited to an almost inconceivably small corner of the universe.

What, then, is life? Is it the final climax towards which the whole creation moves, for which the millions of millions of years of transformation of matter in uninhabited stars and nebulæ, and of waste radiation into desert space, have been only an incredibly extravagant preparation? Or is it a mere accidental and possibly quite unimportant by-product of natural processes, which have some other and more stupendous end in view? Or, to glance at a still more modest line of thought, is it of the nature of a disease which affects matter in its old age, when it has lost the high temperature and capacity for generating high-frequency radiation with which younger and more vigorous matter would at once destroy life? Or, throwing humility aside, is it the only reality, which creates, instead of being created by, the colossal masses of the stars and nebulæ and the almost inconceivably long vistas of astronomical time? There are too many ways even to enumerate of interpreting the conclusions we have reached; I do not, however, think there is any one way of evading them.

THREE LONG PERIOD SPECTROSCOPIC BINARY ORBITS

By R. K. Young.

The determination of the orbits of binary stars whose periods of revolution are long, takes considerably more time than the determination of an equal number of shorter period binaries. The consequence of this fact is that a small proportion of the binaries whose orbits will probably prove long, i.e. stars of the later spectral types, has been completed. For statistical purposes, it is important to have as many late type stars included as possible. The difficulty in determining orbits for many of the late type stars lies not only in the long period but is due also to the fact that if one-prism dispersion is available, the range of variation may be masked by errors of observation. Wherever the indicated range is such as to justify a reasonable expectation of success, we think the star should be included on the observational program.

The following three orbits are based upon observations made with the one-prism spectrograph attached to the 72-inch telescope of the Dominion Astrophysical Observatory. When leaving the observatory in 1924 to take up new duties at the University of Toronto I had obtained sufficient data to complete these orbits but it is only in the past year that I have been able to perform the necessary computations incident to publishing the final results. The detailed description of the stars will apear in the publications of the Dominion Astrophysical Observatory.

4 Ursae Minoris

The star 4 Ursae Minoris, (α1900. $14^h\ 09^m.2$, dec. $+\ 78°\ 01'$) was discovered to be binary by the writer while staying at the Lick Observatory in California in 1909-10. Six plates taken in these two years with a three-prism instrument gave a range in velocity of eleven kilometers. The star is of type *K* and its visual magnitude 5.00. The lines in the spectrum are sharp and well suited for measurement. The absolute magnitude as determined

by Mr. Harper and the writer is 0.7 and the parallax 0.011, so that the star is a giant.

Thirty six plates in all were available to determine the orbit of which six were taken at the Lick Observatory in 1909-10, three at the Mount Wilson Observatory 1917-20 and the remainder at Victoria from 1920 to 1924. The complete interval covers nine revolutions of the star. The elements which are given below are the result of a least square solution in which the period was included. The probable error for a single plate is large, 2.4 km. and the three prism plates taken at the Lick Observatory also yield unusually large residuals. This suggests that there is some disturbing factor to ordinary two body motion. The star would probably repay observation with a higher dispersion.

Period	P	$=575.24 \pm 1.0$ days.
Periastron Passage	T	= Julian Day 2423104.4 $\pm$ 23 days.
Longitude of Periastron	ω	$=287\ .3 \pm 15$
Eccentricity	e	$=0.07 \pm .04$
Semi-amplitude of Range	K	$=+9.49 \pm .38$ Km.
Velocity of System	γ	$=11.57 \pm .59$ Km.
Projected semi-axis major	$a\ Sin\ i$	=91,300,000. Km.
Mass function	$\frac{m_1^3 Sin^3 i}{(m+m_1)^2}$	$=0.11\ \odot$

BD 66° 878

The star BD 66° 878 (α, 1900. $14^h\ 56^m0$ dec. 66° 20′ Mag. 4.9 Type *M7*) was discovered to be a binary at the Lick Observatory in 1909. The absolute magnitude has been estimated to be -0.7. The following orbit rests on a least square solution from 31 observations. The star is interesting in that it has the latest type spectrum for which a spectroscopic orbit has ever been determined. Preliminary results for this orbit have already been presented before a meeting of the American Astronomical Society in 1924. The orbit is sensibly circular and the element T is taken to refer to that instant when the radial velocity curve is crossing the γ axis when the velocity is changing from negative to positive. This is the instant of *perihelion*. The probable error, 1.10 km. for a single plate is quite satisfactory.

Period	P	=750 days
Perihelion Passage	T	=Julian Day 2422065.0±5.3 days
Eccentricity	e	=0 assumed
Semi-amplitude of Range	K	=6.67 Km. ± 0.41
Velocity of System	γ	=+6.85 Km. ± 0.24
Projected semi-axis major	$a \, Sin \, i$	=68800000 Km.
Mass Function	$\frac{m_1^3 Sin^3 i}{(m+m_1)^2}$	=.023 ⊙

β Scuti

The star β Scuti (α 1900, 18 41^{m}8, dec.−4° 51′, mag. 4.5, type *G*6) was announced as a binary by the Lick Observatory from plates taken in 1899 and 1900. The details of their measures were kindly sent to me by Director Campbell by mail. They are ten in number and have been of great assistance in getting the period. Two observations taken at the Bonn Observatory were available also and 18 taken at Victoria. The elements which are well determined are the result of a least square solution and the probable error of a single plate comes out 0.8 kilometers.

Period	P	=834 days
Periastron passage	T	=Julian Day 2422480.9±1.5 days
Longitude of Periastron	ω	=33°.9±1°.3
Eccentricity	e	=0.35.±013
Semi-amplitude of Range	K	=16.65 Km. ±0.27 Km.
Velocity of System	γ	=−21.9 Km. ± 0.17 Km.
Projected semi-axis major	$a \, Sini$	=178,000,000 Km.
Mass Function	$\frac{m_1^3 Sin^3 i}{(m+m_1)^2}$	=0.33 ⊙

SOLAR ACTIVITY AND LONG-PERIOD WEATHER CHANGES.

By H. H. Clayton; Smithsonian Miscellaneous Collections, Volume 78, Number 4.

Reviewed by J. Patterson.

Mr. Clayton has given many years of study to the very important problem of "Solar Activity and Weather Changes". His previous studies were chiefly concerned with short period variations in solar activity and daily weather changes in the Argentine. In the present article he has attacked the problem of solar activity and its relation to long period forecasts in North America.

For this purpose he considered that all monthly mean values of solar radiation below 1.930 gram-calories per min. per sq. cm. were taken as low and all above 1.950 as high. He then obtained the mean monthly departures of temperature from normal for a number of widely separated stations in North America, for two months preceding to twelve months succeeding the occurence of the solar values. This was done for high solar values and for low values, for the winter half-year and the summer half-year. The results did not show a sharply marked effect of the solar radiation differences on the temperature for a single month but he considers that there is an effect on account of the high correlation between the averages of temperature for the interval 0 to 4 months accompanying and following high values of solar radiation and an equal interval for low radiation values. The results indicated that the oscillations at northern stations are opposite in phase to those at southern stations and that there are two pulses accompanying and following each high and low solar value (1) a rise or depression of temperature accompanying high or low solar values and (2) a similar departure about three months later.

As regards the geographical distribution of weather effects of solar variation, he finds that, for increased solar radiation, the pressure during the winter half year rises in high latitudes over the

continental mass of North America, and falls along the southern coast of Alaska and probably over the ocean to the South as well as over the central and western United States, while the temperature falls over Alaska, Canada and the Northern United States and rises south of Latitude 38° down at least to 10° south. The percentage of rainfall is greater with high solar radiation over nearly the whole of North America down to Latitude 35° North and is less south of that. In the summer the differences of pressure and temperature are almost opposite to what they are in the winter.

One great objection to the deductions that have been made above is that there are so few years of solar radiation observations; Dr. Abbot however has shown that the data available indicate that there is a relation between the monthly sunspot numbers and the monthly means of solar radiation and that high sun spot numbers indicate a high solar radiation. Mr. Clayton has used this relationship and has carried back the investigation as far as accurate meteorological observations are available. The results of the two sets of comparisons are very similar and he obtained very much the same geographical distribution of weather phenomena for the high and low sunspot numbers as for high and low radiation values.

Mr. Clayton is convinced from these studies that there is a real relation between weather conditions and the monthly means of solar radiation and sunspot numbers but in the average the amounts of the change in pressure, temperature and precipitation are not large. Either there are large disturbing factors or, as seems more probable, the phase of the effect is not constant at one place, being sometimes positive and sometimes negative, according to some law not yet understood.

Mr. Clayton also attempted forecasts for the daily temperature for New York three, four and five days in advance for a period of two years. These forecasts were based on observed solar conditions and the temperatures observed at two or three stations in the United States; it was agreed to consider all temperatures over 5° above normal as high temperatures, more than 5° below normal as low and the intermediate as normal. The verification for temperatures forecasted for five days in advance showed that the difference between mean temperatures following forecasts of high tempera-

tures and that following forecasts of low temperatures was 2.2° in the right direction. Had the forecasts been perfectly successful the difference would have been over four times as much and if complete failures the difference would have been zero so that Mr. Clayton can claim a certain measure of success.

Since all the energy required for the weather processes is ultimately received from the sun, and if the variations in the solar radiation are ultimately proved to be true and not due to errors in observation or in absorption in the atmosphere, then these variations must have some effect on the weather and this is the problem that Mr. Clayton is trying to solve, but, as he states in his paper, the problem is one of great complexity. If this investigation could be carried out in the laboratory the procedure would be to use controlled experiments in which only one of the factors was varied; but weather processes are on such a vast scale that this cannot be done, and as the weather at a particular place is the resultant of the operation of many factors it seems almost a hopeless task to select one of the factors and obtain its effects without it being completely masked by the operation of the other factors. The temperature, pressure, rainfall, etc., at a place are determined, apart from its geographical and topographical position, by the development and movement of areas of high and low pressure and are thus the end products in the process. Solar radiation variations must be world wide in their effects and without taking into account the process through which the solar radiation is transformed into the weather at a station it does not seem possible to obtain any connection between the two that could be of use in forecasting. The problem is almost an exact parallel to a mathematical investigation in which certain conditions are given and then by a series of equations and transformations a solution is obtained but there is not likely to be any definite connection between the initial conditions and the end products unless the connecting equations are taken into account.

These remarks are not intended as a criticism of Mr. Clayton's paper, but as simply a statement of the problem as it appears to me in order to show its great complexity. He has well expressed my own view when he states: "The phase of the effect (of solar

radiation variation) may not be constant at any one place, being some times positive and some times negative according to some law not yet fully disclosed".

The article is a distinct contribution to the subject and Mr. Clayton is to be congratulated on the way in which he is trying to unravel this complex problem.

Meteorological Office,
Toronto.

REVIEW OF PUBLICATIONS

Astronomy by John Charles Duncan, Professor of Astronomy in Wellesley College, 384 pages, 5½x8½ in. N.Y., Harper and Brothers, 1926. Price $3.75.

This is another modern text-book. It treats the entire subject of astronomy and is intended for beginning college classes. The author has been teaching astronomy during the last sixteen years and has also done a creditable amount of research. As a consequence he has had an excellent training for the task of summarising in a simple way the many rapid developments which have been made in recent years.

Among the subjects discussed are the following:—Temperatures, rotation periods, and climatic conditions of the planets; theories as to the source of solar and stellar energy; the theory of the atom and its applications; the theory of relativity; stellar photometry; the luminosities and distances of stars determined by their spectra; the diameters, masses, and densities of stars; motions of stars, star clusters, and nebulæ; novæ; Cepheid and long-period variable stars; the distances of star clusters and nebulæ; the structure of the visible universe; cosmic evolution.

The book contains 58 full-page plates each having usually more than one photograph on it, one coloured plate of spectra, six star-maps, and nearly 200 figures in the text. There are also numerous tables in the text, e.g., the 40 brightest stars, the 23 nearest stars, stars of rapid motion,—in which are given distances, diameters, masses and much other information.

The book is well printed and should have a large sale. It will certainly increase the interest in the study of the universe.

C. A. CHANT.

NOTES AND QUERIES

Communications are invited, especially from amateurs. The Editor will try to secure answers to queries.

Audibility of the Aurora

In Samuel Hearne's "Journey from Hudson's Bay to the Northern Ocean" (1771) he speaks of the audibility of the aurora in these terms:—

"I do not remember to have met with any travellers into high Northern latitudes, who remarked their having heard the Northern Lights make any noise in the air as they vary their colours or position; which may probably be owing to the want of perfect silence at the time they made their observations on those meteors. I can positively affirm, that in still nights I have frequently heard them make a rustling and crackling noise, like the waving of a large flag in a fresh gale of wind. This is not peculiar to the place of which I am now writing, as I have heard the same noise very plain at Churchill River; and in all probability it is only for want of attention that it has not been heard in every part of the Northern hemisphere where they have been known to shine with any considerable degree of lustre. It is, however, very probable that these lights are sometimes much nearer the Earth than they are at others, according to the state of the atmosphere, and this may have a great effect on the sound: but the truth or falsehood of this conjecture I leave to the determination of those who are better skilled in natural philosophy than I can pretend to be."—p. 224, original edition, (London, 1795); p. 235, Champlain Society's Edition, (Toronto, 1911).—A.F.H.

Sir Christopher Wren's Cipher

In the "Science News-Letter" for December 4, 1926, there was published a cipher which is to be found in Brewster's "Memoirs of the Life and Writings of Sir Isaac Newton". It was found among Newton's papers and was said to have been composed by Sir Christopher Wren and presented by him to the Royal Society on November 30, 1714, when he was over eighty years old, and to describe an apparatus for determining longitude at sea. He died,

however, before he could give a solution, and, so far as is known, none has ever before been published. The cipher is as follows:

OZVCVAYINIXDNCVOCWEDCNMALNABECIRTEWNGR-
AMHHCCAW
ZEIYEINOIEBIVTXESCIOCPSDEDMNANHSEEPRPIWHD-
RAEHHXCIF
EZKAVEBIMOXRFCSLCEEDHWMGNNIVEOMREWWER-
RCSHEPCIP

Prof. Bancroft H. Brown, of Dartmouth College, gives the following solution:—

"Reverse the letters in each paragraph, omit every third letter, the cipher now reads:

WACH MAGNETIC BALANCE WOVND IN VACVO
FIX HEAD HIPPES HANDS POISE TUBE ON EYE
PIPE SCREWE MOVING WHEELS FROM BEAKE.

"The omitted letters spell:

CHR WREN MDCCXIVZ."

Just what sort of apparatus Sir Christopher described is not entirely evident, but Prof. Brown makes the following suggestions:

"On the face of it, I should say that the first sentence refers to a chronometer of particular type, while the second and third sentences refer to a method of obtaining the altitude of a star (possibly the moon, or Jupiter's moons, though there is no clear evidence of either) while at sea. Let me be a little more explicit.

" 'WACH MAGNETIC BALANCE WOVND IN VACVO.' 'WACH' is presumably 'watch'. 'MAGNETIC BALANCE' conveys very little to me, possibly it refers to some device for eliminating magnetic disturbances. 'WOVND IN VACVO' apparently means just that, a chronometer in a vacuum, and wound in the vacuum. Perhaps the winding was to take place by means of a magnet.

" 'FIX HEAD HIPPES HANDS POISE TUBE ON EYE—PIPE SCREWE MOVING WHEELS FROM BEAKE.' This, like the preceding, needs careful study by an expert in mechanical terms and usages of the early eighteenth century. It seems to imply something like this: At some elevated point in the forepart of the ship (BEAKE means bowsprit, or some elevated fixed point) a screw enables a wheel to be moved up and down. The

observer fixes his head in a definite place, poises a telescope (tube), and observes some star; he signals to his assistant to raise or lower the wheel at the beake until he secures an alignment. He thus obtains (from known measurements on the ship) the altitude of the star. This determination, together with the time, is obviously sufficient to determine longitudes."

The "Science News-Letter" asks for further suggestions as to the nature of the apparatus.

HARVARD OBSERVATORY'S SOUTHERN BRANCH MOVES

The Boyden Station of the Harvard College Observatory at Arequipa, Peru, established thirty-eight years ago to study stars in the south celestial hemisphere, is to be moved to South Africa.

The new station will be the third from an American university to be established in South Africa since 1924. Last year, Dr. Frank Schlesinger, of the Yale University Observatory, installed a large telescope at Johannesburg for the measurement of the distances of some of the southern stars. A large telescope belonging to the University of Michigan is now being installed at Blomfontein for the study of double stars.

This instrument has a lens 27 inches in diameter. It was almost completed by McDowell at the time of his death, and was finished by Hageman. After much delay the telescope and its 56-ft dome were completed and shipped to South Africa. Then Professor Hussey and Dr. R. A. Rossiter sailed for England, on the way to Blomfontein, to erect the instrument, but when in London Professor Hussey died, on October 28, 1926. Dr. Rossiter has proceeded to South Africa to take charge of the work. This southern observatory was financed by R. P. Lamont, of Chicago, a friend of Professor Hussey since college days.

C.A.C.

MEETINGS OF THE SOCIETY

AT LONDON

The opening meeting was held on Friday, Sept. 24th at 8.15 P.M. in the Arts Building, University of Western Ontario, Dr. H. R. Kingston presiding.

Dr. Kingston gave an address on the Autumn Skies. By the use of a table with concentric circles on the top surface Dr. Kingston gave a remarkably clear demonstration of the way the sun appears to move among the stars in the course of the year. The relative positions of the Signs of the Zodiac were shown by means of bits of cardboard, also the present location of the planets Mars, Jupiter and Saturn. Lantern slides were used to show the principal star groups which are visible at this time of the year. The lecture called forth a large number of questions which were answered by the lecturer and added greatly to the success of the meeting.

The November meeting was held at the Normal School on Friday, Nov. 19th at 8.15 P.M., Dr. H. R. Kingston presiding.

Messrs. T. C. Benson and F. W. Daly were appointed to audit the Treasurer's books for the year 1926.

Mr. T. C. Benson gave a very interesting talk on Orion. Mr. Benson used two large charts, one to show the mythological figure of the great hunter with his club and lion's skin, the other to locate the principal stars in the constellation. Several interesting bits of legendary lore were narrated. Mr. Benson pointed out that Orion has two first magnitude stars, Betelgeuse and Rigel; five second magnitude stars and thirty-seven other stars visible to the naked eye. Several stars of the group are beautiful double stars, there is a great nebula lying just below Orion's belt.

Dr. E. T. White followed with an address on Variable Stars. A variable star was defined as one whose brightness changes. It was pointed out that the study of variable stars is specially suitable for amateurs and much work of permanent value is being done by this class of observers.

Four classes of variable stars were described, viz., (1) Eclipsing variables of the Algol Type; (2) Eclipsing variables of the Beta Lyrae Type; (3) Long Period variables; and (4) Novae or new stars. Two spheres joined together and made to revolve about their common centre of gravity were used to illustrate eclipsing variables. Graphs were drawn on the blackboard to show the character of the changes in brightness exhibited by the two classes of eclipsing variables. The Algol type, with one bright and one dark star, having each minimum followed by a maximum brightness differs from the Beta Lyrae type composed of two bright stars which show a maximum of brightness but two different minina. Mira was described as the best example of the long period variable. Mira has a period of 332 days, it takes from 70 to 80 days in fading from its greatest

brightness and remains beyond naked eye vision for six months. The cause of its sudden bursting out and increasing in brightness some 1500-fold and then fading away only to repeat the phenomena every 332 days has never been satisfactorily explained. Nova Persei, discovered in 1901, and Nova Aquilae, discovered in 1918, were taken as examples of Temporary or New stars. These stars blaze out suddenly, becoming very bright, and then gradually fade out into very faint stars or become invisible. Slides were used to show the bright nebulæ which appeared with Nova Persei and the changes in brightness exhibited by Nova Aquilæ.

E. T. WHITE, *Sec'y.*

AT TORONTO

The regular fortnightly meeting of the Society was held in the Physics Building on Tuesday, November 16th, 1926.

Mr. A. F. Hunter, in the chair. The minutes of the previous two meetings were read and approved.

Under the heading of Observations, Mr. Miller spoke briefly on the recent opposition of Mars. He called attention to the fact that many confuse the appearance of certain white spots with the polar caps. As Mars' orbit is inclined about 25 degrees to the plane of the ecliptic one polar cap only is clearly visible to the observer at one time.

Mr. Hunter made reference to the Leonid Meteors, whose annual appearance is at the maximum about Nov. 13th. On that date he was rewarded in his watch by seeing one good example early in the morning.

Prof. Chant took occasion to read some interesting correspondence. A letter reached the office of the Society from a gentleman in Alberta seeking some information about a curious old astronomical instrument in the possession of his family. He sent the instrument on to the Society. Mr. Miller after examination, replied giving a very minute description of the origin and uses to which the instrument was put. Mr. Miller described it as a ring sun dial of extremely fine workmanship, evidently the product of an expert craftsman about 200 years ago and he surmised it must have been made for some wealthy gentleman given to travelling abroad.

The paper of the evening was given by Mr. A. F. Miller on the Life and Work of John Flamsteed, the first Astronomer Royal of England, and the founder of Greenwich Observatory.

At the outset of his address, Mr. Miller cited the unique and unusual occurrence in connection with the life work of John Flamsteed, that this man as a youth had sufficient penetration and grasp of the requirements of a scientific career to set down a definite principle which should guide his activities throughout his life, and still more unusual that his immediate successors should follow on with the same guiding principle.

He foresaw that only by constant repetition of careful observations could unavoidable errors be eliminated. Therefore, from the outset his principle was

to pursue a fundamental scheme of practical measurement, the purpose of which should be the attainment of so complete a power of prediction that the places of the sun, moon, and planets may be assigned without noticeable error for an indefinite future time.

It would appear that Flamsteed had almost a mania for autobiography (fortunately for his historians) so Mr. Miller remarked on the accessibility of material for the study of his life.

Born in 1646 near Derby, England, he was a sickly child and all his life more or less afflicted with a rheumatic ailment.

He early showed a bent towards mathematics and in his 'teens occupied his spare time instrument making. Before the age of 20 years he had made a catalogue of 70 stars, calculated an eclipse of the sun, and computed for himself the equation of time. Also one or two of his papers on astronomical subjects were printed a few years later. He compiled an almanac with predictions for the year 1670. These and other accomplishments brought him to the notice of the Royal Society and through this connection he later was appointed by King Charles to the honour of being his Astronomer. The appointment carried with it the yearly income of $100. The Observatory was designed and built by Sir Christopher Wren.

The important work of his life was his catalogue of about 3,000 stars and his lunar observations.

Flamsteed was contemporary with Halley and Newton. Both men, but especially Newton, had a great influence on his character and life. A quarrel with Newton marred to some extent the excellence of his work.

The paper throughout was exceedingly interesting and informative. Mr. Miller has the wonderful faculty of adding the personal touch to the characters he is picturing. These great men of genius, of whom we are wont to stand in awe, were revealed to us as men of like passions as ourselves.

After some discussion and remarks of appreciation the meeting was adjourned.

November 30th, 1926—The evening was given over to "popular astronomy," the subjects being Experiments in Light, and Motion Pictures dealing with Light, followed by films showing Time and the rotation of the Earth, the Fallacy of Perpetual Motion, The Birth of the Earth, etc.

Professor Chant demonstrated, by use of a lantern and prisms, how a ray of white light was separated into its different wave-lengths, and the colour effects he produced were very much appreciated by the audience, which completely filled the lecture room and showed great interest. Several members contributed to the discussion of recent observations, chiefly of meteors and cloud effects.

The General Secretary introduced the motion pictures with a few remarks of explanation, and quoted some recent comments by authors of astronomical works on the subject of Light, its speed, and added some illustrations of the distances of the stars and nebulæ as measured by the light year.

A. KENNEDY, *Recorder.*

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